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Review Article

Assessment of Pulmonary Edema: Principles and Practice

Sherif Assaad, MD[*,1], Wolf B. Kratzert, MD, PhD[†], Benjamin Shelley, MD[‡], Malcolm B. Friedman, MD[§], Albert Perrino Jr, MD[*]

[*]*Cardiothoracic Anesthesia Service, VA Connecticut Healthcare System, Yale University School of Medicine, New Haven, CT*

[†]*Department of Anesthesiology and Perioperative Medicine, David Geffen School of Medicine at University of California at Los Angeles, Los Angeles, CA*

[‡]*Golden Jubilee National Hospital /West of Scotland Heart and Lung Centre, University of Glasgow, Glasgow, Scotland*

[§]*Department of Radiology and Biomedical Imaging, Yale University School of Medicine, VA Connecticut Healthcare System, New Haven, CT*

Pulmonary edema increasingly is recognized as a perioperative complication affecting outcome. Several risk factors have been identified, including those of cardiogenic origin, such as heart failure or excessive fluid administration, and those related to increased pulmonary capillary permeability secondary to inflammatory mediators.

Effective treatment requires prompt diagnosis and early intervention. Consequently, over the past 2 centuries a concentrated effort to develop clinical tools to rapidly diagnose pulmonary edema and track response to treatment has occurred. The ideal properties of such a tool would include high sensitivity and specificity, easy availability, and the ability to diagnose early accumulation of lung water before the development of the full clinical presentation. In addition, clinicians highly value the ability to precisely quantify extravascular lung water accumulation and differentiate hydrostatic from high permeability etiologies of pulmonary edema.

In this review, advances in understanding the physiology of extravascular lung water accumulation in health and in disease and the various mechanisms that protect against the development of pulmonary edema under physiologic conditions are discussed. In addition, the various bedside modalities available to diagnose early accumulation of extravascular lung water and pulmonary edema, including chest auscultation, chest roentgenography, lung ultrasonography, and transpulmonary thermodilution, are examined. Furthermore, advantages and limitations of these methods for the operating room and intensive care unit that are critical for proper modality selection in each individual case are explored. Published by Elsevier Ltd.

Key Words: pulmonary edema; auscultation; chest radiography; lung ultrasound; transpulmonary thermodilution

THE LUNGS REPRESENT unique organs in which air and blood are circulating efficiently, each in its own conduit without mixing with one another. Air circulates in the lungs' bronchial and alveolar conduits that are surrounded by blood circulating in a permeable and pressurized capillary network. Normally there is a balance between the net fluid filtered from the pulmonary circulation and the fluid absorbed by the lymphatic system. This balance ensures that only a small volume of fluid is present in the interstitial space. Excessive accumulation of extravascular lung water (EVLW) is clinically manifested as pulmonary edema. This can result from an increase in the amount of filtered fluid secondary to marked increases in pulmonary hydrostatic pressure or an increase in

[1]*Address reprint requests to* Sherif Assaad, MD, VA Healthcare System, Department of Anesthesiology, 950 Campbell Avenue, West Haven, CT 06516.

E-mail address: sherif.assaad@yale.edu (S. Assaad).

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the pulmonary capillary permeability, which causes water and proteins extravasation,[1] or from interruption of the lymphatic drainage, such as what occurs in lung resection surgery.[2] Regardless of the etiology, the resultant fluid accumulation in the lung impairs respiratory gas exchange, resulting in respiratory distress and the need for mechanical ventilation.

Pulmonary edema increasingly is being recognized as a perioperative complication affecting outcome. Several factors have been identified (eg, fluid overload, systemic inflammatory response to surgery, myocardial ischemia, blood product transfusion), all of which contribute to increased fluid transudation and accumulation of EVLW.[3] Management strategies directed at avoiding excessive fluid administration (eg, goal-directed fluid therapy) or reducing inflammatory response (eg, protective lung ventilation to avoid ventilator-induced lung injury) commonly are advocated in perioperative care protocols.[1,4–7]

Furthermore, pulmonary edema represents a significant burden to the health care system. A review of 8,195 patients who underwent major inpatient surgeries in two university teaching hospitals revealed an incidence of pulmonary edema of 7.6% with an associated in-hospital mortality rate of 11.9%.[8] Pulmonary edema is associated with higher morbidity rates and prolonged intensive care unit (ICU) stay, in which 15% of those diagnosed with pulmonary edema will require mechanical ventilation.[9] Furthermore, the addition of mechanical ventilation will extend the length of stay in the ICU.[10] As such this complication often results in a lose-lose proposition because it worsens patient outcomes while greatly increasing health care costs.[11]

For decades, chest auscultation and roentgenography played a major role in the diagnosis of pulmonary edema and in monitoring response to therapy. The understanding of the inherent limitations of these 2 methods has led to the development of newer technologies that offer more sensitive detection of lung water changes in real time to better aid diagnosis and guide clinical interventions.[12] Of these, both the lung ultrasound (LUS) and transpulmonary thermodilution (TPTD) methods have now entered the clinical arena. The aim of this review is to provide an up-to-date examination of the recent advances in understanding the physiology of lung water dynamics in health and disease and to highlight the various bedside methods available to measure EVLW and diagnose pulmonary edema. Special emphasis is placed on the emerging roles of LUS and TPTD as new tools to quantitatively measure EVLW in the perioperative period and provide early diagnosis of pulmonary edema.

Current Concepts in Pulmonary Fluid Dynamics

Extravascular Lung Water in Health and Disease

It is a remarkable feat of engineering that prevents the air-filled alveoli and surrounding interstitium from being soaked by the neighboring pulmonary vessels. Pressurized and highly permeable, there is a strong motive force driving pulmonary capillary fluids across the microvascular endothelium into the interstitium and air sacs. Yet the interstitium is a relatively dry space with an EVLW of < 10 mL/kg of ideal body weight.[13]

The mechanism controlling fluid exchange between the microvascular and interstitial spaces proposed by Ernest Starling in 1896 shaped medical thinking for more than a century. He concluded that the interplay of outward filtration forces created by the capillary hydrostatic pressure and the inward reabsorption forces from plasma protein oncotic pressure determines fluid exchange, with the capillary endothelium acting as a semipermeable membrane.[14]

Although this model became widely adopted as doctrine, a series of experimental data beginning in the 1940s raised doubts on its merit. The discovery that an endothelial surface layer lining the luminal side of the capillary endothelium, as first described by Danielli 1940,[15] and the nonlinear relationship between hydrostatic pressure and vascular permeability, which represents a deviation from the classic Starling relationship, revolutionized the understanding of fluid dynamics.[16–18]

Electron microscopy shows that the endothelial surface layer is lined with a complex network of glycosaminoglycans and proteins, which creates a gel-like coating. The structure of this endothelial surface layer is called the endothelial glycocalyx (EG) (Fig 1).[19] The EG recently has been discovered to play a critical role in capillary fluid dynamics, preventing excessive fluid extravasation. First, it acts as a molecular sieve limiting water and solute efflux across the intercellular junction. Second, it provides scaffolding on which serum plasma proteins accumulate and consequently a layer of ultrafiltrate is created between the endothelium and the EG. This layer of ultrafiltrate creates a powerful oncotic force, pulling fluid to the intravascular compartment. Breakdown of this layer, such as after surgical trauma and ischemic/reperfusion injuries, results in markedly increased capillary permeability (Fig 2).[17] Lastly, the EG acts as a mechanosensor, transmitting the shear stress from blood flow to the endothelium cytoskeleton and initiating intracellular signaling, which increase capillary permeability.[16,20] After a marked increase in capillary hydrostatic pressure, fluid extravasates out of the capillaries and accumulates in the interstitial space.

The emerging role of the EG has reshaped the current understanding of the pathophysiology of pulmonary edema. Either damage to this EG layer or marked increases in capillary hydrostatic pressure will lead to excessive fluid transudation into the interstitial space.

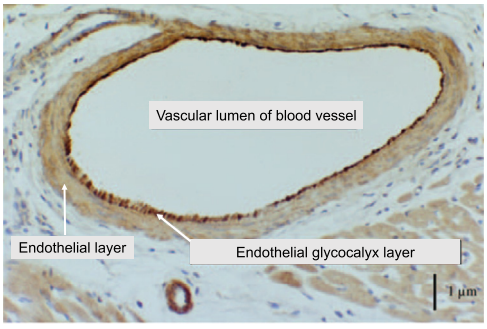

Fig 1. Electron microscopy reveals vascular capillary in cross-section and its associated EG layer. Adapted from Rehm et al.[19]